NASA's Public Participation Universe: Why and How the U.S. Space Agency Is Democratizing Its Approaches to Innovation

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This paper analyzes NASA's increasing effort to invite greater public participation in its technoscientific work through open innovation methodologies. First we examine why NASA has expanded its use of these approaches, noting the roles of an intertwined set of forcing functions including budget constraints, the growth of scientific data, availability of technological resources, political climate, and committed individuals. Next we outline the strategies the agency has invoked to engage the public in research, technology development, and other activities to advance and shape NASA's mission. As we show, promoting greater public involvement has entailed facilitating the NASA workforce's familiarity with open innovation approaches as well as developing projects and creating outreach strategies appropriate to the envisioned participant base. We then discuss the wide variety of outcomes NASA's open innovation initiatives have yielded in support of NASA research and development objectives as well as benefits to participants and others. We conclude with a discussion of the remaining barriers to the use of open innovation techniques as a standard practice and the strategies in work to overcome those barriers so the full potential of a democratized approach to innovation can be realized.

I. Introduction

The notion that individuals should be regarded not only as consumers of science and technology but also as active participants in shaping innovation processes is gaining increasing recognition from government agencies, non-governmental organizations, corporations, and citizens alike. Citizens, regardless of their scientific and technical backgrounds, have proven on many occasions that they possess important knowledge, skills, and values that professionals may lack but bear on the ability to address effectively pertinent issues. The academic literature teems

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with accounts of productive participation by "non-experts" as co-creators alongside credentialed scientists and technologists in technoscientific innovation and policy choices (see, for example, Epstein 1996; Callon, Lascoumes, and Barthe 2009; Jasanoff 2004; and Wynne 1996).[1-4]

The National Aeronautics and Space Administration (NASA) has led the United States' civil space program for more than a half-century. NASA's founding legislation, the National Aeronautics and Space Act of 1958, requires the agency to "arrange for participation by the scientific community in planning scientific measurements and observations" and "provide for the widest practicable and appropriate dissemination of information concerning its activities and results." Citizen participation, however, is not explicitly called out, and is a relatively new and evolving concept since the turn of the 21st century. In fact, U.S. space exploration is a domain whose primary narrative depicts a government-controlled activity with little room for involvement by entities other than NASA officials and other U.S. government policy makers, established aerospace companies, and credentialed space scientists.[5-6] Most historical accounts depict NASA's interactions with American citizens outside of government agencies and aerospace firms since the 1950s and 1960s as efforts to "sell" its human spaceflight initiatives and to position citizens as would-be observers and supporters of such activities rather than as active participants.

The range of actors participating in NASA projects has in fact evolved and grown over time. During the Space Shuttle era, NASA began to engage with new publics as users of the vehicle and substantive contributors to its success.[7] Today, the agency increasingly accommodates more active roles for new entities in the nation's space program. Students of various levels are now routinely invited to participate in developing payloads to fly on sounding rockets, high-altitude balloons, and space-bound vehicles. NASA also has enlarged its focus on partnering with the growing commercial space industry as part of its operational model. The agency has moved to a model of purchasing cargo and crew flights to the International Space Station (ISS) on vehicles owned by private companies. In addition, NASA encourages commercial use of the ISS, including through its partnership with the Center for Advancement of Science in Space (CASIS) as well as pursuing increased opportunities to reach a more diverse set of partners through the novel use of traditional procurement practices such as broad agency announcements.

Equally notably, the agency has with increasing frequency been looking for participation beyond commercial firms and the academic sphere and is also inviting the broader national, and in many cases international, citizenry to help solve technological problems and contribute to the advancement of space-related science. NASA's latest strategic plan acknowledges individual members of the public as partners in its work, much as it has long depended on industry, academia, and international space agencies to advance goals in space.[8] Over the past decade, NASA has established a suite of initiatives, policies, funding streams, organizations, and communities aimed at facilitating the agency's use of "open innovation" approaches to engage members of the public in lending their skills, ideas, enthusiasm, and time to advance particular goals and objectives. NASA has welcomed individuals to collect and analyze scientific data, make discoveries, develop technologies and data applications, and solve complex problems. The agency has involved members of the public as volunteers in the scientific process (in what are often referred to as "citizen science" projects) as well as through data hackathons, problem-focused challenges and prize competitions, and public deliberations. In fact, NASA has been recognized by the White House Office of Science and Technology Policy as a leader within the U.S. government in embracing new forms of public involvement.

This paper analyzes NASA's increasing effort to invite greater public participation in its technoscientific work through open innovation methodologies. First we examine why NASA has expanded its use of these approaches, noting the roles of an intertwined set of forcing functions including budget constraints, the growth of scientific data, availability of technological resources, political climate, and committed individuals. Next we outline the strategies the agency has invoked to engage the public in research, technology development, and other activities to advance and shape NASA's mission. As we show, promoting greater public involvement has entailed facilitating the NASA workforce's familiarity with open innovation approaches as well as developing projects and creating outreach strategies appropriate to the envisioned participant base. We then discuss the wide variety of outcomes NASA's open innovation initiatives have yielded in support of NASA research and development objectives as well as benefits to participants and others. We conclude with a discussion of the remaining barriers to the use of open innovation techniques as a standard practice and the strategies in work to overcome those barriers so the full potential of a democratized approach to innovation can be realized.

II. Contributing Factors

Most of NASA's achievements to date have entailed enlisting traditional entities and strategies to meet its space and aeronautics research and technology development objectives. In addition to the roles NASA's own scientists, engineers, and program managers play in the design, development, testing, and operations of spacecraft and aeronautics systems and an assortment of scientific research and technology projects, much of this work is directed and/or funded by NASA to be undertaken by experts in academia and private companies of all sizes through mechanisms including contracts, cooperative agreements, and peer-reviewed grants. It is through the efforts of NASA's collaborations with these entities using these specific approaches that the world witnessed humans landing on the Moon, spacecraft reaching the depths of our solar system, and telescopes peering into the early origins of the universe. Indeed, NASA's relationships with its traditional partners remain strong and vital to addressing outstanding scientific questions and technological needs.

During the Space Shuttle program, even as NASA continued to depend on previous industry partners to develop and operate the Shuttle, NASA began to expand involvement in the program to new groups of people. Seeking approval from the Congress for the next major U.S. human spaceflight project to follow the Apollo program, President Nixon promulgated the Shuttle as a vehicle that would serve the interests of many segments of society. NASA set out to realize that vision by creating opportunities for new types of payloads and people to fly on the spacecraft. Just a few years into the start of Shuttle flights in the early 1980s, NASA could point to a range of new payload owners -- from pharmaceutical companies to high school students to artists -- and people -- from both genders and a multiplicity of genders and professions -- as participants in the space program.[9] The space agency has similarly continued to broaden participation in the use of the ISS. Evolving technological, economic, social, and political developments over recent years have led to a resurgence of the space agency's efforts to augment the players and methods on which it has relied in sustaining this progress and pursuing its objectives with new approaches involving more groups of people.

Growth in NASA's mandate and the demands for NASA to continue to advance space science and space systems, which in turn have become increasingly sophisticated and complex, has been a major factor prompting the space agency to consider new modes of innovation, including increased public involvement. U.S. national leaders, space professionals in academia, as well as aerospace industry affiliates continue to recognize the advancement of space science and technology vis-a-vis the mission and work of NASA as a crucial aspect of U.S. global leadership and economic growth. President George W. Bush recognized the significance of the U.S. space program when in 2004 he announced his Vision for Space Exploration, an ambitious initiative to return humans to the lunar surface and then send them on to Mars. NASA recognized that the magnitude of the technical challenges it would encounter would require the agency to not only look to its own workforce, traditional partners, and international space agencies for contributions but also to stimulate creative ideas using alternative methods. At the time, prize competitions to spur technology development were coming to the fore of government consciousness. The National Academy of Engineering had issued a report in 1999 that stressed the historical value of prizes for this purpose and recommended that the Congress encourage federal agencies to "experiment more extensively with inducement prize contests in science and technology."[10] Meanwhile, the X Prize competition to develop and launch a reusable human-tended spacecraft to space twice within two weeks was underway and the Defense Advanced Projects Research Agency (DARPA) was preparing to conduct its first DARPA Grand Challenge for the development of an autonomous vehicle with a $1 million prize purse. NASA had already begun working on legislative authority to conduct prize competitions and consequently established the Centennial Challenges program of prizes for specific achievements in alignment with the Vision.[11] The program received Congressional authorization in 2005, thus codifying NASA's ability to use appropriated funds for prize competitions open to citizen from all backgrounds and levels of education and making the space agency a government pioneer in the use of this open innovation approach.

Other NASA programs have also turned to open innovation methods such as prize competitions and problem-focused challenges for a number of other reasons. The need to do more with fewer resources is an incentive to look outward for new ideas and new possibilities. While the Vision for Space Exploration promised a funding windfall for the development of new vehicles to support deep space human exploration as the Space Shuttle program came to a close, not all NASA program budgets fared well. The Space Life Sciences Directorate at Johnson Space Center, for

one, endured a budget reduction from $330 million to $175 million in 2005 that resulted in losses of personnel and funds available for making research grants.[12] The drastic cut in turn prompted the directorate's leadership to seek out collaborations and partnerships, including those afforded through open innovation techniques, as a means to make research and technology progress in the area of human health and performance in space. Their efforts included extensive analysis of the program's needs and open innovation technique options that would address their needs and formulation of partnerships with online platforms to issue problem-focused research and technology development challenges. [13] The Johnson team launched dozens of challenges to elicit public responses to its needs. As a direct result of the success of these pilots, competitive procurements were issued that resulted in contracts with open innovation vendors for the use of their expertise and platforms. The successful pilot also resulted in a contract with Harvard Business school to operate the original NASA Tournament Lab to conduct empirically based research into the use of crowd-based competitions for software and algorithm development and how best to apply that technique within an organization.

The complexity of scientific research data and data requirements has also served as a driver for some NASA scientists to look to public participation as a means to advance their research projects. NASA's space telescopes, planetary exploration spacecraft, and Earth-observing satellites provide powerful capabilities for understanding our planet and universe through the enormous volumes of data they produce daily. Mission science teams, however, receive far more data than they can process and analyze on their own. In some cases computer algorithms are not sufficient for detecting the kinds of patterns scientists wish to detect in spacecraft imagery, and therefore direct human involvement remains essential. Other scientists may apply for grants to analyze collected data, but even so the amount of data available to be mined exceeds resources available within NASA and the science community. Some scientists have thus attempted to extend the community's abilities to process data sets by inviting the public to cull through certain data sets in expressly designed "citizen science" projects. Some NASA scientists have found utility in welcoming the public to make astronomical or environmental observations to augment or validate measurements made by spacecraft on orbit. NASA has also engaged the public in mining the space agency's data through open hackathons, such as the International Space Apps Challenge, as a means to generate creative ideas about what kinds of applications can be derived from NASA data. In a recent study on mass collaboration innovation drivers based on data from Space Apps participation, the authors found that the intensity of competition in a challenge framework increases the level of innovative potential and output.[14]

Still other conditions have contributed to NASA's pursuit of greater public participation in its work. NASA has long sought to connect with people around the globe as a means to inform and educate about its space and aeronautics activities -- and the introduction of social media offered new tools to engage with new audiences and communities. From its inception, the space agency tapped the news media, civic groups, and schools to share its achievements with the worldwide public. Skylab program managers in the early 1970s took the first step in involving one segment of society -- high school students -- in space research as experimenters aboard the Skylab space station. As new communications and information technologies have become available, NASA demonstrated an early willingness to adopt alternative ways to engage still other segments of society. NASA sponsored a Participatory Exploration Summit in April 2007 to meet with technology and social media start-ups to look at ways to include citizens using platforms and tools coming onto the market from Silicon Valley. Participatory Exploration, defined by the organizers from the Space Operations Mission Directorate and Innovative Partnership Office at NASA Headquarters and the Ames Research Center, was a concept for the public to collaborate with NASA to share ideas to spur innovation. Leveraging the internet, social media, collaboration platforms, and the ubiquity of smartphones -- tools that were simply unavailable decades ago -- is allowing the space agency to reach enormous numbers of people around the globe directly, not only for the purpose of disseminating information about its activities but also to involve them in the agency's research and development work. Indeed, NASA program managers are beginning to recognize the ability to achieve innovation as well as outreach and education aims through citizen science projects, challenge and prize competitions, and data hackathons. These approaches are enabling NASA to connect with people who have long had strong interest in space activities to become direct contributors to the space program while also reaching beyond space enthusiasts to people with an array of backgrounds, interests, and skill sets that could prove valuable to NASA's needs.

NASA's increasing use of open innovation approaches also has been sustained and substantiated through a political climate favoring public participation in government operations. NASA's early open innovation experience predated but was coming into its own before President Obama entered office. The Obama Administration commitment to increasing transparency, collaboration, and public participation in federal government operations supported and helped to spur further the legacy already in place at NASA.[15] The 2010 Open Government Plan laid a framework for citizen engagement by creating cross-cutting agency objectives: to increase transparency and accountability to external stakeholders; enable citizen participation in NASA's missions; improve internal NASA collaboration and innovation; encourage partnerships to create economic opportunity; and institutionalize open government philosophies and practices at NASA.[16-17] In developing the 2010 Plan, NASA engaged with citizens, asking for ideas on how to participate. More than 1200 citizens participated, offering 420 ideas. NASA responded with programs such as High Schools with NASA can Create Hardware (HUNCH) which allowed students to develop hardware from excess equipment on the International Space Station which they detect from live video feeds from space inside the orbiting outpost. NASA created the International Space Apps Challenge in 2012 as a way to convene citizens to leverage NASA's storehouse of data to to create innovative projects that can contribute to their communities as well as provide insight or new thinking for NASA's mission-related challenges. [18] The agency gained and maintained momentum to pursue still other challenge and prize competitions and citizen science activities as well as to invite the public to express preferences concerning the future direction of its asteroid research programs through the Administration's ongoing efforts to develop policies and resources to support federal agencies in their adoption of open innovation methods. At the same time, NASA's successes have helped to advance government-wide open innovation efforts. Aware of NASA's experience with challenge and prize competitions, the Office of Science and Technology Policy asked NASA to establish the Center of Excellence for Collaborative Innovation (CoECI) as an institution that could support all federal agencies to expand their use of open innovation methods. NASA's authority to conduct prizes through the Centennial Challenges program, meanwhile, laid the foundation for other federal agencies to attain similar authorities through the America COMPETES Act.

Lastly, another key factor explaining why the Centennial Challenges program, the NASA Tournament Lab, and dozens of challenges, prize competitions, and citizen science projects have emerged in recent years as new approaches to innovation is that individuals within NASA believed in and championed their adoption as a means to bring new ideas and contributions into the space agency. NASA is an enormous organization made up of some 18,000 civil servants and many support contractors. Initiatives and ideas of all kinds take root when individuals recognize a need or opportunity to do new things or to do things differently as a means to improve effectiveness or efficiency and take action to convince others of the same and make changes happen. Several such individuals at NASA are to credit for advocating open innovation approaches and starting these initiatives within the space agency.

III. Strategies for Employing Open Innovation Approaches

Extending NASA's innovation toolbox to include open innovation approaches has required agency policy officials and practitioners to modify practices they have applied in pursuing in-house research and development, peer-reviewed grants, contracts, and other agreements. The researchers and program managers who have adopted these approaches have had to think differently about how to find solutions to problems that concern them and how to interact with new types of participants. NASA officials have taken a number of steps to facilitate employees' use of open innovation methods. This section elaborates three overarching strategies NASA is using to advance the use of open innovation approaches. The first two reflect steps being taken by project managers who adopt these practices, while the third articulates how NASA is aiding employees' ability to use these approaches effectively.

A. Matching Methods to Needs and Purposes

Scientists and engineers must consider carefully how to design any research and development project to ensure their methods will allow them to gather the data or arrive at a solution that meets their technical and cost requirements. Involving the public through an open innovation project is just one of multiple avenues available to NASA scientists, engineers, and program managers for addressing their needs. Sometimes public participation is not an appropriate means of pursuing a research problem or technology development challenge. This can be particularly true when, for

example, a NASA researcher's, engineer's, or program manager's data contain elements that are subject to privacy regulations or technology is subject to international traffic in arms (ITAR) restrictions.

When an individual does wish to consider the possibility of incorporating public participation into a project, the reality is that open innovation is an umbrella term comprising a variety of different methodologies. NASA has adopted and developed a range of different ways in which to invite public participation in its work. Individual scientists, engineers, and program managers select the specific approaches they use based on their needs.

1) Crowdsourcing of scientific tasks (citizen science)

Inviting public participation can allow scientific researchers to extend their ability to make observations in disparate geographic locations by relying on people already in those locations for assistance. Access to many regions on Earth to make measurements has been particularly useful to create a global view of phenomena that affect or occur throughout the Earth system. NASA, in partnership with other federal agencies, supports the Global Learning and Observation to Benefit the Environment (GLOBE) program, which draws on the participation of tens of thousands of schoolchildren and other members of the public to take standardized measurements of air temperature, water pH, soil moisture, and other environmental parameters to create a worldwide map of these conditions. The GLOBE team has recently introduced a "GLOBE Observer" mobile phone app to encourage more individuals to make environmental measurements in their communities. The app will incorporate a longstanding NASA project which invites participants to take and send in photographs of clouds that NASA researchers can use to validate measurements taken by overhead satellites; more projects will be added to the app over time. NASA also leverages public observations of astronomical phenomena. The JunoCam project has invited amateur astronomers worldwide public to upload their images of Jupiter and discuss features of interest and help with planning what images will be taken by the Juno spacecraft currently in orbit at Jupiter. The public will also aid in processing the images once acquired.[19]

Crowdsourcing also enables researchers to accelerate significantly the time required to analyze images or data returned from space when computer algorithms are not sufficient to detect patterns of interest and human judgment is required. The Stardust@home project welcomes participants to search online microscope images for interstellar dust particles trapped in the aerogel collectors of the Stardust spacecraft, which returned to Earth in 2006. Similarly, hundreds of thousands of people worldwide have taken part in searches of imagery taken by NASA's planetary spacecraft and space telescopes. NASA-funded researchers have established projects such as Planet Four, which allows participants to identify windswept terrains on Mars, and Disk Detective, which invites the public to find dusty disks around stars where planets may be forming or existent. With the assistance of so many volunteers, researchers can process data far more quickly than they could if they had to do the jobs alone. The Disk Detective project enabled the classification in one year, with the aid of thousands of public participants, the same number of telescope images a single researcher would have needed eleven years to review. These projects also benefit from showing the same image to multiple individuals so that they can get multiple opinions on the features appearing in an image -- a level of review researchers would not have if evaluating images alone. In addition, there have been several instances where data were thrown out by automatic computer algorithms as flawed or corrupted when in fact the data were valid and an object of particular significance would have been overlooked without the intervention of citizen scientists. An example of this is the Kepler spacecraft observations of KIC 8462852 (nicknamed "Tabby's Star"), which was discovered by citizen scientists participating in NASA's Planet Hunters program and has become an object of intense study and speculation by the scientific community and public alike. Developers of these crowdsourced research projects employ several techniques to safeguard data quality; in addition to sharing each image with multiple participants, they often include providing tutorials to participants before they begin classifying images and keeping interfaces simple for soliciting participant inputs.

2) Challenge and Prize Competitions

Opening a problem to the crowd can also help generate a broader range of solutions than one might obtain through a contract or award to a single entity and often for far lower cost. The use of prize

competitions linked to particular challenges or problems can allow NASA to evaluate a wide range of potential solutions, bring out-of-discipline perspectives to bear, avoid needing to predict in advance which team or approach is most likely to succeed, and make payments only after participants demonstrate results. NASA offers different competition programs for long- and near-term needs.

Centennial Challenges, NASA's flagship challenge program, offers incentive prizes to generate revolutionary solutions to problems of interest to NASA and the nation. The program seeks innovations from diverse, multi-disciplinary and non-traditional sources. Competitors are not supported by government funding and awards are only made to successful teams when the challenges are met. In keeping with the spirit of the Wright Brothers and other American innovators, the Centennial Challenge prizes are offered to wide variety of participants (in teams or individuals) including ordinary citizens as well as those in academia, industry, and other government agencies. These inventors are sought to generate innovative solutions for technical problems of interest to NASA and the nation and to potentially stimulate or create new business ventures. Because many technical problems have multiple solution pathways, prize competitions allow more designs to be experimentally demonstrated than a standard contract or grant.

NASA has learned that in order to have successful and productive challenge competitions, there are several areas that need to be addressed upfront. The areas include: starting with clear objectives; having simple rules that are published in a Request for Information (RFI) for public feedback before the challenge is announced; and minimizing the need for expensive testing, verification, or qualitative judging. A White House Office of Science and Technology Policy's report analyzed public-sector prize competitions and challenges and found that in fiscal year 2015 the public sector was using prize competitions and challenges more often and using partnerships to make them more ambitious. In the report, the NASA Centennial Challenge Cube Quest competition was used as one of the examples of how federal agencies are hosting more challenges with technology development-driven goals and using partnerships to plan more sophisticated challenges. [20] From 2005 to date, the program has conducted 15 challenges in technology development areas including: propulsion, robotics, communication and navigation, human health, destination systems, science instrumentation, nanotech, materials and structures, and aerodynamics. Eleven of those challenges have produced winners from 35 different teams that have won a total of $6.532 million. In fiscal year 2016, to date, the program has completed four competitions from three challenges; Cube Quest Challenge, Mars Ascent Vehicle Challenge and Sample Return Robot Challenge (Level 1 and 2); and has opened two new challenges for registration: Vascular Tissue Challenge and Space Robotic Challenge. The program is also reformulating the Phase 2 and 3 of the 3D Printed Habitation Challenge and is working on the development of six possible new challenges, targeting various NASA technology needs.

Growing out of the original pilot conducted at Johnson, CoECI competitions launched through the NASA Tournament Lab (NTL) platforms are structured based on NASA's procurement authority. These challenges are designed to acquire a solution that directly supports an identified, and occasionally short-term, operational need within a specific project. CoECI crowd-based competitions have a much smaller monetary award than Centennial prize competitions, are significantly shorter-term in length, are open to international participation, and executed as a contractual requirement by a company whose business model is based on successfully incentivizing participation by a diverse population of individuals. NTL challenges are the selected company's responsibility to fully execute inclusive of paying the winners, if winners are selected. The companies also are engaged in negotiating the IP rights associated with the winning solution: usually an unlimited license for government use or an open source license with the software and/or algorithm then housed on NASA's GitHub repository.

Partnerships play an important role in the administration and success of many external prize competitions. Centennial challenges often involve a partnership with an allied organization that brings expertise to the specific technology development target area and assumes responsibility for the administration of the competition. These partnerships are often with non-profit entities that have the ability to raise awareness and funding to support execution of the competitions, which can, and often do, involve technology demonstration events. For example, NASA partnered with Worchester Polytechnic Institute to administer the Sample Return Robot competition that boasts a $1.5 million prize purse. NASA also partners with entities

that bring particular technical or scientific expertise to the subject discipline of the particular challenge. NASA partnered with Planetary Resources, Inc., to launch the Asteroid Data Hunter challenge through the NTL on the Topcoder platform. Planetary Resources contributed expertise to the overall design of the challenge in addition to providing access to a culled data set that accelerated architecting and conduct of the algorithmic element of the challenge. Conversely, NASA has entered into partnerships where they provide the expertise and subject matter experts for a competition conducted by an external entity where there may or may not be a cash prize. For example, NASA currently has a partnership with the American Society of Mechanical Engineers, which in turn uses the Future Engineers organization to launch 3D design challenges for K-12 students aligned with the in-space manufacturing initiative examining the use of 3D printing in space. Examples of other competition-based strategic partnerships in the academic realm include the Rice University Business Plan Competition and the National Space Grant Foundation's eXploration Habitat (X-Hab) Academic Innovation Challenge.

3) Hackathons

A hackathon is a gathering of individuals to address specific challenges through collaborative computer programming. NASA's first experience with a hackathon dates back to 2009 under the umbrella of a unique collaboration between NASA, Microsoft, Google, World Bank, and Yahoo to address topics around disaster management. Random Hacks of Kindness (RHoK), a 2010 NASA Open Government initiative, supported "Hacking for Humanity" to build a volunteer community of innovation to leverage technology to address pressing global issues. The International Space Apps Challenge, an annual 48-hour hackathon event, was born out of the RHoK experience with the intent to build an innovation community around space-related challenges. Space Apps is unique in the federal space in the model community involvement. NASA gathers the subject matter experts, cleans up datasets, and convenes the challenges, while the local communities host the event by raising funds, securing the venue, managing the logistics, outreach and local volunteers. Space Apps grew from 25 locations in 2012 to 161 locations in 61 countries with over 15,000 global participants in 2016. Hackathons have grown in popularity and become a staple in citizen science and open innovation toolkits widely used by federal agencies. Most often, federal hackathons do not offer cash prizes but rather provide citizens an opportunity to innovate around agency open data and open source code. Some teams come to the event pre-formed, but most convene around topics of shared interest and complementary skills. Hackathons have broadened from the original appeal to software developers, and now appeal to artists, designers, storytellers, policy strategists, and hardware specialists. The diverse skills and experiences gathered into hackathon teams help generate unexpected, creative, and compelling solutions that often surprise technical experts within the agencies. Though a solution developed in 48 or 72 hours may not look as polished as a contract-derived product, the ideas behind the solutions may be transformative when applied to agency processes. Serendipity occurs when scientists and technologists allow citizens to contribute to the problem-solving process.

In the case of Space Apps, the 1,300 solutions created in 2016 alone, may generate only a handful of tangible follow-on projects within NASA organizations and projects -- just like a thousand photographs may only yield the one money shot. These few gems, though, are proof the process works. As NASA subject matter experts review the team solutions to hackathon challenges, they express interest in participating in future activities. From the participant's perspective, their engagement with NASA brings them new insights on the relevance of space research and encourages them to grow their skills to come back to team again for future events. Winning teams return as hosts and step up to grow innovation within their local communities. A study by Fatima Senghore and her colleagues looked at the hackathon mass collaboration model through the lens of innovation drivers. In addition to competition, they assessed hackathon-specific network vitality at individual locations and social interaction for co-located teams as opposed to virtual teams. Using social network analysis from the first two years of Space Apps, they found increased vitality in terms of higher numbers of participants and project solutions at recurring locations; they also noted that geographic separation had no bearing on innovative output.[21] As Space Apps matured, the phenomenon of event success

with recurring hosts was borne out. These hosts organized larger and more sophisticated events and stepped up to mentor new hosts, creating regional clusters of innovation. They also signed on to host pre-event training sessions for participants new to hackathons as well as follow-on accelerator activities to support promising local teams. The Space Apps hackathon model sparked tiny innovation communities around the value proposition that NASA data were available to apply not only to agency challenges but also to community concerns. NASA opened the door to community-wide innovation efforts that live on beyond the annual event.

Not only did the International Space Apps Challenge spark innovation in local communities around the world, it also sparked innovation internally as citizens served as an unintended, and unexpected, focus group on NASA's open data initiatives, pointing out the pain points with unlocking the data, as well as social constraints to engagement. NASA listened to feedback from participants each year and worked to refine and enhance the experience, from adding more capabilities for data engagement through the data.NASA.gov website to adding new initiatives to increase participation among women and girls. NASA recognized the need to enable citizen data engagement opportunities in more frequent intervals that require less time commitment. The NASA Datanaut initiative enables a year-round micro-hackathon environment where small teams can engage with challenges each month on their own timing. In addition, beginner coders can engage with experienced classmates to learn new skills and perspectives. Datanauts are provided data engagement toolkits to host data dinner clubs that respect the time constraints of busy professionals who hesitate to commit to a hackathon weekend. Datanauts follows the Space Apps model where they host the event in their communities using NASA data and tools. This initiative is part of the continued experiment to learn how to engage citizens with seeds of NASA data that can take root and grow innovation where they live.

4) Citizen input/deliberation

NASA has always been a "can-do" organization, reliant on its abilities to achieve ambitious scientific and technological goals with the support of long-established academic and industry partners. The agency has typically regarded members of the public beyond these entities as having entrusted the agency to act on their behalf and to whom to announce achievements with the aim of educating them and convincing them of NASA's value. This relationship with the public stemmed from NASA's interpretation of language in the National Aeronautics and Space Act, the agency's originating 1958 legislation, which directs the agency "to provide for the widest practical and appropriate dissemination of information."

Over the past few decades, NASA has conducted a few town hall meetings to solicit public opinion of the agency and space exploration in a general sense and some focus groups to gauge public opinion of NASA. In 2010, NASA leveraged a citizen engagement tool provided by the General Services Administration called IdeaScale for the first time to collect input and comments about NASA projects. More than 1,200 individuals cast nearly 5,000 up or down votes on 420 ideas submitted into the platform. IdeaScale has been a frequently used platform over the years to gain citizen input on various mission-related topics. NASA also has applied a technique called participatory technology assessment to collect public views to inform a specific project in development. In 2013, NASA issued a request for information seeking, among other concepts, ideas for how to broaden participation in the agency's nascent Asteroid Initiative, which seeks to catalog all asteroid threats to Earth and know what to do about them as well as to prepare for human exploration of an asteroid. One idea, which came from a consortium called Expert and Citizen Assessment of Science and Technology (ECAST), entailed conducting a series of opportunities for members of the American public to meet, discuss, and register their views and values concerning NASA's plans for the Asteroid Initiative. NASA entered into an agreement with ECAST to conduct two such forums in November 2014 in Phoenix, Arizona, and in Boston, Massachusetts. Through these forums, NASA demonstrated a process for eliciting public perspectives "upstream" in NASA project development, ahead of key decisions, marking a first not only for NASA but also for the U.S. government.[22]

METHOD	NEED/PURPOSE	PROJECT EXAMPLE(S)
Crowdsourcing of scientific research (citizen science)	Data collection	GLOBE/GLOBE Observer, JunoCam, Target Asteroids, Aurorasaurus
	Data analysis	Stardust@Home, Disk Detective, Planet Four, Planet Hunters
Challenge/prize competition Hackathon	Data application development	International Space Apps Challenge, Datanauts
	Software/algorithm/ development	International Space Station Food Intake Tracker; Asteroid Data Hunter; Lunar Mapping and Modeling Portal; Planetary Data Systems Cassini Rings
	Hardware prototype development	Centennial Challenges (e.g., Astronaut Glove Challenge); International Space Apps Challenge
	Concept/idea for research/technology advancement	Bioinspired Advanced Exercise Concepts; Mars Space Pioneering: Achieving Earth Independence
	Engineering/Research Project Design	Measurement of Kevlar Strain, Non-invasive Measurement of Intracranial Pressure; Mars Balance Mass Challenge
Citizen input/ deliberation	Collection of external views re: NASA policy/program choices	Asteroid Initiative Citizen Forums

Table 1. Open innovation methods used by NASA to achieve various needs and purposes

B. Reaching participants and building communities

A key significant difference between open innovation and NASA's traditional means of research and development is the base of participants solicited and involved. With open innovation NASA is reaching beyond scientists and engineers based at universities and in private companies and is tapping into the talents and interests of all sorts of people, from computer coders to garage tinkerers to students and others. Whereas NASA limits research grant and contract awards to U.S. entities, most of the agency's open innovation projects do not follow national boundaries. Anyone anywhere may win a challenge competition offered through the NASA Tournament Lab, while crowdsourced data collection projects such as Aurorasaurus, which asks people to report their sightings of the Northern Lights, depend on international participation for their success.

Turning to open innovation, however, has required NASA to forge new ways of interacting with would-be participants. NASA has established rules and regulations for awarding grants, contracts, and other agreements to external entities to conduct research and development work. The agency solicits competitive proposals for such work in publications such as the Federal Register and online at grants.gov and fedbizopps and makes awards on the basis of peer review and the careful evaluation of the quality, feasibility, and risks associated with the proposals it receives. Academic institutions and private companies, meanwhile, have experts who await these opportunities and have extensive experience in the technoscientific areas for which NASA is seeking to make awards. They have staffs that watch daily for these announcements, attend any relevant pre-proposal conferences NASA sponsors, and know how to write competitive proposals. In other words, both NASA and its traditional partners have well-established means of working together to fulfill the agency's needs for innovation.

Most members of the public outside of NASA's traditional partners, however, do not regularly review the publications and websites federal agencies use to make solicitations. Reaching them, therefore, has prompted NASA to look to other avenues to communicate opportunities. NASA is looking for prospective participants in open innovation

projects where they are online, using social media and other broadly accessible and widely visited platforms to share opportunities. For example, all NASA challenge and prize competitions are posted to the federal government's challenge.gov website, where those interested in such opportunities know they can find an assortment of challenges that span federal agencies. The agency also uses web platforms frequented by computer coders, such as Topcoder and InnoCentive, to invite participation in challenge and prize competitions to develop software algorithms. By launching competitions on platforms of companies who specialize in curating particular crowds often discipline- or community-based, NASA can tap into that company's expertise in how to incentivize and attract the right participants without relying solely on a targeted outreach campaign. Twitter has become a popular medium used by several NASA citizen science projects for getting the word out about opportunities to participate. While specific projects have their own Twitter handles, NASA is also sharing these project opportunities and developments through the use of the NASA Solve Twitter handle and website (@NASASolve; www.nasa.gov/solve). NASA Solve is NASA's online "one-stop-shop" conveying all of the current participatory opportunities the agency is supporting. Individuals can search NASA Solve for projects according to their specific interests in NASA science and technology.

In some cases, NASA has worked to transform open innovation activities into projects sustained by partners in the communities that participate in them. The International Space Apps Challenge is a unique model that grew into an organic ecosystem of enthusiastic volunteers around the world. In fact, 78% of the 161 local hosts in 2016 were returning event hosts from previous years. With this model, NASA relies on collaboration and distributed authority across hundreds of volunteer organizers worldwide -- with no funding from NASA to aid their efforts. Individuals willingly contribute their time and talent to the Space Apps community each year. NASA serves as the convener, providing the framework for Space Apps' success; outlining the vision and priorities; setting the challenges; and providing guidelines and best practices for hosting the local Space Apps events. Local volunteer organizers do the heavy lifting to plant Space Apps in their own cities. Individuals host Space Apps either because they learn about the opportunity through the community or because they attended as participants in previous years. Interested individuals submit an application to NASA. Once approved, the organizer builds a local team; secures the venue, technology resources, and local collaborators; and manages logistics, event promotions, and local team judging. NASA's Space Apps Global Team provides support to the local organizers with toolkits, planning calls, and general guidance and encouragement -- especially for new organizers. Most amazing is the growth of individuals and communities through participation in Space Apps. Participants become organizers. Organizers become mentors to create regional hubs. Local businesses come together to support the hackathon event but also to nurture promising Space Apps teams. And organizers work with the community to build innovation incubation and acceleration capabilities to support teams year-round.

Building non-traditional participant bases has also involved other considerations. In the absence of peer review and proposal evaluations, NASA has needed to determine how to ensure that those they are engaging have the tools and abilities to complete the projects they pursue. In the case of challenge and prize competitions, the proof of capabilities is in the contestants' abilities to deliver solutions that meet the particular problem posed; even then, NASA project developers must articulate clear specifications and requirements for competitions. Citizen science project developers have the additional challenge of needing to control for quality in the data participants contribute or analyze and do this by keeping participant tasks and interfaces simple and providing tutorials to introduce them to the project. NASA has also sought to encourage involvement of greater numbers of people, including those with little experience, to participate in its data hackathons. The agency has hosted data boot camps as "pre-events" to educate participants about NASA data and its uses; women have often been the focus of these events, and NASA has aimed to facilitate their involvement by offering childcare throughout the events. The agency created the Datanauts program to bolster its community of data applications developers. When conducting citizen deliberation forums in 2014 around its Asteroid Initiative, NASA provided read-ahead materials and video introductions to the topics as well as included facilitators to promote balanced discussion among participants so that all felt empowered to register their views.

C. Providing support to NASA employees to use open innovation

Over the past dozen years, NASA has supported scores of challenge and prize competitions, citizen science projects, and hackathons. Even so, open innovation methods are still not widely ingrained in NASA's research and

development culture. Space scientists, like other science professionals, continue to highly value achievements by individuals including funding awards received and papers accepted by peer-reviewed journals. NASA's can-do attitude, fostered in the agency's early years focused on besting the Soviet Union in human spaceflight achievement, pervades the agency's engineering community. Alternatives to do-it-yourself approaches are at best not well understood by many within NASA and at worst regarded by them as suggesting NASA's inability to solve a problem.[23]

Advocates of open innovation approaches within NASA have instituted policies and practices and other infrastructural changes within the agency to create greater awareness among NASA's workforce about open innovation methods and their utility to the types of problems they seek to solve. One of the earliest institutional support mechanisms for open innovation that NASA introduced was the Center of Excellence for Collaborative Innovation (CoECI). NASA established this virtual center of excellence at the specific request of the White House Office of Science and Technology Policy (OSTP), given NASA's successful pioneering work using crowd-based competitions as an innovative procurement strategy, and made this resource available to not only NASA but also all federal employees. Over the years, CoECI has entered into contracts with an expanding set of companies in the business of hosting online crowdsourced competitions that range from software and algorithm development to engineering and multimedia design. CoECI staff is also able to advise those inside NASA and other federal agencies in determining how a crowdsourced competition could meet their stated need.

NASA has also aimed to build awareness among and offer encouragement and support to employees to embrace open innovation methods using other means. NASA codified its encouragement for agency-wide use of open innovation approaches in an internal policy directive in 2014. [24] In addition, the agency has established a dedicated staff position to promote and coordinate the agency's use of challenges and prize competition, a staff member who directs the Centennial Challenges program, an open innovation manager in the Office of the Chief Information Officer, and a citizen science coordinator in the Office of the Chief Scientist. These individuals work in conjunction with others who recognize the merits of open innovation to educate employees across NASA about the value of these approaches to research and development. Because a major challenge to gaining acceptance of open innovation practices within NASA is the workforce's lack of familiarity with the tools and concerns about their ability to contribute effectively to NASA research and technology development needs, these staff take the time to meet with personnel in various NASA organizations to explain the capabilities afforded by open innovation methods. NASA's prizes and challenges program executive has provided seed funding matched to a NASA office's program funds to conduct pilot prize competitions in areas that have not previously undertaken such efforts, while the Centennial Challenges program fully funds prize competitions. Operated by CoECI, NASA@Work is an internal-only, no-fee platform that provides employees an opportunity to gain experience and a level of comfort with a competition-based approach. NASA@work competitions often lead to a desire to then take a particular problem to an external platform and crowd. NASA also maintains a citizen science community of practice that enables those interested in crowdsourced science activities to meet regularly to learn about citizen science projects underway across the agency and new project funding opportunities as well as to discuss issues faced by citizen science project managers.

IV. Outcomes

As we showed in Section II, NASA scientists, engineers, and program managers have adopted open innovation methods out of recognition that inviting public participation can expand capabilities and opportunities available to fulfill a variety of research and development needs. When examined closely, these approaches in fact can yield numerous, wide-reaching outcomes that include providing support to achieve particular technoscientific purposes -- assistance with research activities, solutions to specific problems, or ideas or inputs relating to program plans -- but also extend beyond those specific intended aims. Scholars and practitioners interested in open innovation have documented a multitude of outcomes that have stemmed from projects that have included public participants, revealing that such projects can result in benefits to the project developers as well as participants and others.

Gustetic et al. (2015) identified seven outcomes that NASA challenges and prize competitions have realized.[25] Crowdsourced data collection and analysis projects, hackathons, and public deliberations also may result in these and additional outcomes. We integrate these outcomes in Figure 1 to offer a broad picture of the impacts these open

innovation initiatives have produced. Figure 1 shows that some outcomes relate to support of NASA's needs, some reflect benefits to participants and others, and some serve NASA as well as participants and others. We discuss how NASA open innovation activities are realizing each of these outcomes.

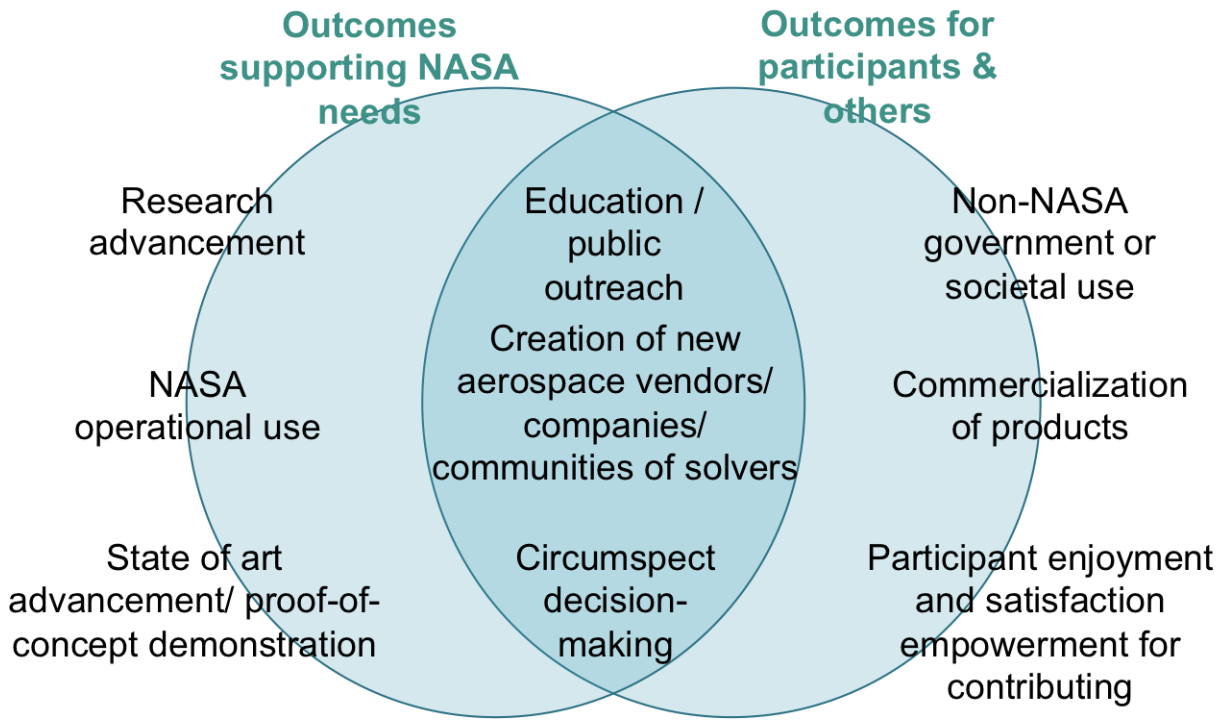

Figure 1. Outcomes associated with the use of open innovation methods

A. Research advancement

A major outcome of NASA's use of open innovation methods has been to yield new information of value to scientists, engineers, and NASA program managers. Crowdsourced science projects have resulted in an array of scientific discoveries published in academic journals. For example, the Aurorasaurus project, which invites individuals to report sightings of aurora (Northern or Southern Lights), has contributed to refining understanding of where aurora will appear, which can contribute to better predictive models of solar events that could impact electrical grids on Earth.[26] Target Asteroids! is a citizen science project that allows amateur astronomers to contribute to understanding the physical properties of near-Earth asteroids. Participants' contributions of observations have contributed directly to understanding of carbonaceous asteroids and their possible connection to (101955) Bennu, the NASA OSIRIS-REx asteroid mission target and (162173) Ryugu, target of the Japanese Hayabusa 2 mission. Citizen scientists participating in the Galaxy Zoo project, which uses some NASA telescope data, discovered an entirely new class of high-redshift galaxies nicknamed "Green Pea" galaxies due to their unusual spectral energy distributions. Since this discovery was announced in 1999, Green Pea galaxies have been the subject of dozens of scientific papers. In addition, a paper has recently been accepted to the *Astrophysical Journal* announcing the discovery of 37 new planet-forming disk candidates discovered by citizen scientists involved with the Disk Detective project.

Challenges and prize competitions can also produce information a competition sponsor did not previously know or result in a greater understanding of the solution space for a particular problem area. Ideas or potential solutions generated through these approaches have included, for example, new ideas for secondary payloads that future Mars-

bound spacecraft could carry without sacrificing mass and a result that accelerates development of a non-invasive technique to measure intracranial pressure to potentially reduce the risk of spaceflight-induced vision changes. The successes of these efforts can be seen in the form of algorithms developed to find anomalies and features of interest in the rings of Saturn that are not otherwise detectable by a computer due to false-positive or in an easily downloadable application that allows citizen scientists to find otherwise undiscovered asteroid threats.

B. Operational use

Another outcome of open innovation methods, particularly challenge and prize competitions, is NASA's incorporation of a proposed solution into direct operations. NASA recently uploaded to the International Space Station an iPad app developed through a prize competition to be used by astronauts to more easily track their food intake in order for NASA scientists to more accurately assess nutrition-related countermeasures to spaceflight-induced risks. The Lunar Mapping and Modeling Portal, also produced through a competition, now processes images in three hours compared to the previous nineteen. The Human Health and Performance Directorate at Johnson Space Center has deployed the crowdsourced-developed Solution Mechanism Guide to its employees to aid their decision-making in which legal mechanism can most effectively advance their specific project, be it grant, contract, or prize competition. CoECI in a preliminary assessment of the results of its crowd-based competitions surmises that 93% of the competitions launched resulted in successful solutions. Of that 93%, 54% of those solutions are in use or implemented.

The Digital Government directive requires NASA to "unlock the power of government data to spur innovation across our Nation and improve the quality of services for the American people." For NASA's open innovation initiatives around open data, citizen engagement to spur innovation is the overarching outcome -- independent of the project solutions citizens create from NASA's open data. The results of a hackathon weekend may not be ready for immediate application; however, the thinking behind the citizen-generated solution may be transformational for NASA project managers. It is important to bound expectations, depending on the challenge or prize format, that the outcome may not be comparable to a well-funded procurement. Some challenge formats are better suited for ideation projects to allow project managers to cast the net widely for new thinking that can be incorporated in the mission. Other projects may seek a highly specified widget that can be plugged directly into a project. The point behind citizen collaboration is to supplement organizational expertise and traditional methods with the serendipity of unexpected solutions from non-traditional resources: citizens.

C. State of art advancement/proof-of-concept demonstration

As NASA continues to pursue its journey to Mars, advancing state-of-the-art techniques that address the need for new technological capabilities and human risk mitigation is tantamount to success. For example, increased intracranial pressure is the leading hypothesis associated with the spaceflight-induced vision changes recently discovered. Using both a prize-based competition and open innovation technology scouting, the research team identified an algorithmic technique that advanced their current development of a non-invasive method to measure intracranial pressure. Not only did the team gain significant research advancement, but also the winner of the competition is now engaged as a principal investigator in on-going efforts. Since 2013, NASA's Disruptive Tolerant Networking (DTN) team has turned to crowd-based competitions to develop data networking protocols that can extend the internet into the solar system. As reported by OSTP, the DTN Security Key architecture completed in 2014 produced a capability previously not available – "no security organizations had figured out how to do it and it was unclear at the outset if it could be done."[27]

D. Education/public outreach

In the process of collectively involving tens of thousands of people, including many students, these methods have also proven their worth as innovative ways to fulfill NASA public outreach and education aims. In 2014, the Academic Affairs Office at NASA's Marshall Space Flight Center conducted the Human Exploration Rover Challenge to engage high school and college students in a competition to design, construct, and test rover technology that could be used in extraterrestrial environments. The challenge was launched specifically to engage a new community in NASA's efforts to explore planets, moons, asteroids, and comets, but also served to provide students with valuable hands-on experience in the development of concepts and technologies that could support future missions. Similarly, the Future Engineers 3D

Design Challenges for K-12 students focus on solving real-world space exploration problems. Students are asked to submit 3D model designs of 3D printable objects for an astronaut theoretically to use in space. The challenge series was developed to provide students with access to NASA's first 3D Printing in Zero-G ISS Technology Demonstration aboard the International Space Station. The challenges provide students with NASA mission-related design and research problems to assist with advancing NASA's technical capabilities. Submissions are judged on innovation and creativity of the solution, the ability to advance human space exploration, and the ability to communicate the design and quality of the 3D model through a text description and an interview. To date the level of maturity these students demonstrate in both design and demeanor and the excitement they bring to working on a NASA-specific problem is testament to an outcome that incentivizes the next generation of NASA researchers and engineers.

E. Creation of new aerospace vendors, companies, and communities of problem solvers

In addition to producing tangible products and ideas for NASA's consideration, open innovation projects have contributed to developing new cadres of human capital and talent to support space-related research and development. In the realm of citizen science, the Disk Detective project has benefitted from super users who have formed a community of enthusiastic participants who can converse knowledgeably with the science team. Disk Detective has enjoyed participation by more than 28,000 individuals, who have made nearly 1.5 million image classifications of more than 278,000 disk candidates. Participants have also translated the website into eleven languages. As noted previously, the Space Apps challenge created an entire community of individuals and teams willing to support this yearly initiative. Several of the companies that have been engaged with launching challenges associated with the NASA Tournament Lab have noted increased numbers of individuals and teams signing up to participate in their competition-based initiatives as a direct result of NASA competitions.

Also, as noted by OSTP in its 2014 report on the use of prizes in the federal sector,

"Incentive prizes can be powerful tools for supporting entrepreneurs and small businesses by leveling the playing field and giving license to pursue an endorsed stretch goal that otherwise may have been considered overly audacious."[28]

NASA's Centennial Challenges program is intentionally structured to offer independent inventors including small businesses, student groups, and individual incentives to participate in technology development that has a long-term benefit to NASA but that may also have potential for commercialization. The Centennial program has supported the development of several new small businesses now serving the aerospace industry including Flagsuit LLC, Final Frontier, LaserMotive, Masten Space Systems, to name a few.

F. Circumspect decisionmaking

Open innovation projects that are intended to solicit public views can contribute to agency decision-making. NASA processes tend to favor cost; schedule, technical feasibility and risk, and the ability push the boundaries of scientific knowledge or space exploration as parameters to determine whether to pursue a project. The participatory technology assessment ECAST conducted on NASA's behalf allowed NASA to take note of public views and values concerning options for near-Earth asteroid hazard detection and mitigation and approaches to human exploration of an asteroid as well as Mars. The results of the deliberation forums were shared with NASA managers for consideration as they planned for Asteroid Initiative research and development activities. [29-30]

G. Non-NASA government or societal use

As highlighted by Gustetic et al., the Centennial program's astronaut glove challenge is a stellar example of how NASA's open innovation activities can prove valuable for uses outside of NASA's immediate needs.[31] This challenge focused on development of an astronaut glove design to reduce the effort required by astronauts to perform tasks during space walks. The winners of this dual-phased challenge produced highly improved pressure-suit glove technology and went on to found two companies engaged in the development of pressure suits or components for private non-NASA spaceflight companies. Yet another example comes from the International Space Apps Challenge and its focus on open source solutions to mission-related challenges. Citizens use NASA open data to create solutions

for their own use in their own communities. For instance, a team from Kathmandu created a crowd-sourced community trash app that allows citizens to photograph trash, mark it with a geo tag, and upload it for city government. City workers could use the app to locate trash for collection. The Galactic Impact global winner from Italy in 2016 created the L.I.V.E Glacier Project, a crowd-sourced sustainable tourism app to provide glacier information and share photos of the changing glaciers landscape, combined with the Live Ice Velocity Estimation Glaciers web tool that provides near real-time visualizations of glacier surface velocity fields, using images from SENTINEL-1 Synthetic Aperture Radar images and NASA GIBS. London team Canaria, the 2016 global winner of the Best Use of Hardware, created a 3D printed earpiece with a CO_2 monitor patch that acts as a lifeline to the wearer, simultaneously monitoring the wearer's heart rate, blood oxygen, and environmental air quality. The earpiece can be worn on Space Station to alert crew members of dangerous conditions, and can also be worn by miners to detect ventilation problems, or hospital patients to allow health data collection for medical staff.[32-33]

H. Commercialization of products

Yet another outcome of some NASA open innovation projects is the commercialization of resulting products. Gustetic et al. highlighted that the Centennial Lunar Lander Challenge was designed to accelerate technology developments supporting the commercial creation of a vehicle capable of ferrying cargo or humans back and forth between lunar orbit and the lunar surface.[34] Such a vehicle was expected to have direct application to NASA's space exploration goals as well as the commerical spaceflight industry. With only a few days remaining in the 2009 competition period, Masten Space Systems of Mojave, California, successfully met the more complex level requirements for the competition and by posting the best average landing accuracy, won the first place prize of $1 million. Since the Lunar Lander competition interest in vertical takeoff and landing with commercial suborbital launch vehicles has grown. Shortly after the competition Masten was awarded a Department of Defense Small Business Innovation and Research contract to use their vehicles in network communications testing. In 2012, the NASA Flight Opportunities Program initiated the development of a commercial landing technology demonstration test bed. Draper Laboratory, of Cambridge, Massachusetts, was selected to lead this effort. Draper Lab subsequently selected Masten Space Systems to provide the vertical takeoff and landing flight vehicle to demonstrate this new landing technology. Masten is now active in the commercial space environment.

I. Participant enjoyment, satisfaction, and empowerment through contributing

One outcome of NASA open innovation projects specific to participants is the satisfaction they derive from participating in such activities. Crowdsourced research projects, challenges and prize competitions, hackathons, and public deliberations provide members of the public opportunities to bring their enthusiasm, skills, and ideas to bear on NASA science and technology programs and directions. Consistent with scholarly research that has found the same, participants in these NASA activities have reported time and again that their involvement has given them enjoyment, satisfaction, or a feeling of empowerment for making a contribution to the work of the nation's space program. These views have been indicated in a variety of ways. When ECAST ran the Asteroid Initiative citizen forums on NASA's behalf, the partner conducted pre- and post-surveys to measure how participants were affected by their experience at the forums. Post-surveys showed that participants were highly satisfied with their involvement in the deliberations. Others' enthusiasm for participation has been evident in their commitment to NASA's open innovation projects. For example, the Disk Detective project has some participants so engaged in the activity that they have online chats about the phenomena that they observe, and one participant drove across South America to participate in a ground-based telescope observing run of a candidate object identified through the Disk Detective project.

The International Space Apps Challenge team collects feedback from participants each year to add to the annual report. For instance, Bijaya Dongol of Kathmandu stated,

"I thought NASA was only concerned in exploring space. But Space Apps made me believe that NASA is also concerned in encouraging creativity of people."[35]

Sam Yang from Managua said,

"I loved the global nature of the event and NASA's support of fresh, innovative thinking."[36]

Louise Dennis from the United Kingdom stated,

"For the first time, my 11-year-old daughter and my husband attended [Space Apps]. This was my daughter's first time at a hackathon event and she really loved it and felt included as if she had a real contribution to make."[37]

Courtney Wiggins of New York said,

"Prior to the challenge, I didn't give NASA (and space for that matter) much thought. However, after listening to the wonderful stories and experiences from the women of NASA and interacting with NASA staff, my interest in NASA programs is heightened. I look to teach my young son more about NASA and space from this experience because it's tangible to me now."[38]

And finally, Helene Bilaud of Quito organizer offered this insight,

"Do you know what it means for students who are from a small town to mingle with people who are alike and are actually allowed to think big and believe they can have an impact on other people's lives? We saw this spark in every single participant this weekend. Thank you for letting them believe in themselves and see that they are part of something much bigger."[39]

V. Conclusion

NASA is a leader among federal agencies in the exploration of public engagement opportunities. Long before public engagement became popular in the federal sphere, NASA spearheaded the use of social platforms to allow members of the public not only to participate but also to collaborate with how NASA determined priorities for future opportunities. Pioneers of the open innovation movement at NASA have served as early adopters of cutting edge methods and practices for others to follow suit. These efforts have not been easy as new practices create uncertainty and disruption within the status quo. However, with persistence, these methods and practices are beginning to take root and flourish in organizational pockets across NASA. These pioneers have paved the way for others to follow, by creating toolkits and support mechanisms to ease their path to success. As the social media revolution, technology, and political climate made citizen engagement more accessible and acceptable, more NASA organizations are willing to try out these techniques.

Obstacles do remain to NASA's widespread acceptance of and reliance on public involvement in research and innovation. Such obstacles include, for example, convincing scientists and engineers throughout the agency of the worthwhileness of committing limited resources to try new approaches involving unfamiliar communities and individuals to advance their projects. As we noted in this paper, initiatives and ideas of all kinds take root when individuals recognize a need or opportunity to do new things or to do things differently as a means to improve effectiveness or efficiency in their own work areas. Convincing managers, scientists, and engineers of the value of taking on these new approaches, often perceived as either additional work on top of already resource-constrained efforts, or unproven methodologies requires patience and perseverance on the part of the agency's open innovation advocates working to infuse these techniques. Deliberate strategies that include either incentivizing through seed funding or directing funding to be used for an open innovation project are required to further instantiate the practice along with the continued pursuit of opportunities to share the growing body of proven success. Communication strategies have been developed that emphasize the outcomes in a manner that speaks directly to the day-to-day work of the research and engineering teams so they can understand the possible applicability to their own specific work. We have considerable distance to go before it is common practice that yearly budget submits include an abundance of

open innovation projects, but we remain convinced of the benefitsof open innovation methods and believe their adoption as a standard practice is a worthy and realistic achievement.

Lastly, we reiterate that engaging the public in NASA's technoscientific work through crowdsourcing and other methods can only be effective when project developers appropriately align their aims and expectations, the capabilities of their intended participants, and the design of their projects. These considerations are critical to ensuring success, whether defined as the generation or analysis of data of suitable quality to produce valid results or the creation of a promising technological prototype to achieve a specific NASA objective. Even so, our experience to date has proved that the serendipity of unexpected outcomes from citizen solutions can open new insights and new opportunities for engineering and scientific advances that could not have been anticipated in the program design. No matter what the initial outcome of the open innovation method applied, citizens continue to surprise us. Based on our experience to date, members of the public will continue to play an important role in NASA's expanding innovation universe.

Acknowledgments

The authors would like to thank Karen James for formatting this paper for submission, and Sarah Becky Ramsey for her constant and dedicated outreach efforts in support of NASA's open innovation community.

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